Insertion, Validation, and Application of Barotropic and Baroclinic Tides in 1/12 and 1/25 Degree Global HYCOM

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LONG-TERM GOALS

A partnership of institutions (academia and government) is collaborating on inserting and validating barotropic and baroclinic tides in 1/12° and 1/25° numerical simulations of the global ocean. The collaboration is applying the results of the 1/12° and 1/25° simulations to a number of problems of scientific interest, described in further detail below. This partnership builds on the strong relationship that the lead PI of this proposal, Brian Arbic, has established since 2006 with Florida State University (FSU) and the Stennis Space Center branch of the Naval Research Laboratory (NRL) . NRL and FSU have a long-standing relationship, developed during the National Oceanographic Partnership Program (NOPP)-supported HYCOM (HYbrid Coordinate Ocean Model) consortium effort, to develop and transition an eddy-resolving, real-time global and basin-scale ocean prediction system. These systems are being transitioned for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS. This project builds upon work begun with Naval Research Laboratory contract N000173-06-2-C003, and reported on in Arbic et al. (2010).

OBJECTIVES

The partnership is utilizing global HYCOM, run at horizontal resolutions of 1/12° and 1/25°, with barotropic and baroclinic tides inserted into an eddy-resolving ("eddying") circulation. Thus far, most of the global NRL simulations that include tides have been forward simulations, that is, simulations without data assimilation. The NRL group has shown that the data assimilation procedure they currently use on non-tidal motions can be used in simulations with embedded tides without "breaking" either the non-tidal motions (i.e. the eddying general circulation) or the tides themselves. The next step is to perform data assimilation on the tides as well. The NRL group is currently testing schemes to assimilate tides into eddying HYCOM. Since the goal of operational models is high accuracy, we have endeavored to create forward models that achieve a high level of accuracy in the tides before the data assimilation is inserted. In this way, the data-assimilative models build upon an accurate foundation laid by the forward models.

As an important first step in improving the forward tide model, the horizontal resolution of HYCOM simulations containing eddies and tides simultaneously has recently been increased to 1/25°. New simulations at this resolution are already running on DoD machines. The higher resolution simulations

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are in line with stated U.S. Navy goals to have a 1/25° resolution version of the HYCOM ocean prediction system, with tides, available in the near future for Navy operational purposes.

The topographic wave drag scheme utilized in the model is currently being retuned by NRL collaborators and in the future will be further improved through use of the statistical roughness field produced in a separate Office of Naval Research (ONR) grant (John Goff and Brian Arbic, N00014-07-1-0792 and N00014-09-1-1003, "Effects of small-scale bathymetric roughness on the global internal wave field"; Goff and Arbic 2010). As shown by a number of authors, topographic wave drag is critical to the accuracy of forward tide models.

Scientific applications of the wind-plus-tides simulations will be investigated during the course of this proposed research. For instance, the three-dimensional global tidal velocity and isopycnal displacement fields in HYCOM will be compared to those measured by current meters. The sea surface height signatures of internal tides in HYCOM have been validated globally against satellite altimeter measurements. The temporal stability (stationarity) of the internal tide signals at the sea surface in the face of mesoscale activity has been examined. The aliasing of internal tides into the mesoscale band in satellite altimeter data, and the resulting contamination of altimetry-derived internal tide data, will be examined through sampling exercises with the model. The impact of internal tides on sea surface height wavenumber spectra has been documented, with implications for the development of the proposed wide-swath satellite altimeter (NASA/CNES SWOT mission). Three-dimensional maps of internal-wave driven energy dissipation and mixing will be developed from the HYCOM simulations. Parametric subharmonic instability and tidal energy fluxes in HYCOM are being examined by Joseph Ansong, an NSF-funded postdoc. Frequency spectra of sea surface height from the model has been compared to spectra obtained from tide gauges, on timescales from hours to years. Frequency spectra of model kinetic energy have been compared to spectra obtained from current meters, also on timescales from hours to years, and nonlinear wave-wave interactions in the model have been computed in the frequency domain. The model has been used to estimate errors in the computation of vertical models from vertically sparse historical current meter records. We will display some of our results on these topics below. Finally, Arbic and his UM team will collaborate with NRL and FSU on the introduction and validation of data assimilation into the HYCOM tide simulations, and with both NRL and FSU on the FSU-based HYCOM data server. Regarding the latter point, we will specifically examine how to optimize the storage of HYCOM output on the server at high spatial resolution (1/25° global) when tides are included, which traditionally leads to much higher temporal sampling than is done in models which do not include tides.

APPROACH

We insert tides into HYCOM following the techniques outlined in Arbic et al. (2004), which can be consulted for extensive discussions on global tide modeling. The astronomical tidal potentials of the eight largest tidal constituents, adjusted for the effects of solid-earth body tides (e.g., Hendershott 1972) were entered into the momentum equations. For our first simulations self-attraction and loading (Hendershott 1972, Ray 1998) was parameterized using the simple scalar approximation (Ray 1998). Current simulations being done by our NRL collaborators include an iterative procedure utilizing the full spherical harmonic treatment of Hendershott (1972). Topographic wave drag, which represents energy loss due to breaking of internal waves generated by tidal flows over rough topography, is also inserted into the model momentum equations. This has been common practice for forward tide models since the pioneering effort of Jayne and St. Laurent (2001). With the drag scheme incorporated, HYCOM captures about 92% of the sea surface elevation variance of the eight largest tidal

constituents as measured by a standard set of 102 pelagic tide gauges (Shum et al. 1997). This level of accuracy for the barotropic tides is comparable to that seen in previous carefully tuned forward tide models, e.g. Arbic et al. (2004).

The key individuals involved in this research are:

--Brian K. Arbic, UM, PI of this grant: Arbic is in frequent contact with the individuals listed below as we continue to research tides in HYCOM, and is a critical actor in coordination of the overall HYCOM tides effort. Arbic is also working with Maarten Buijsman and Alan Wallcraft of NRL to improve several aspects of the HYCOM tides simulations, including self-attraction and loading, topographic wave drag, implementation of the first schemes for tidal data assimilation, and examination of the impact of stratification on the barotropic tidal field. We have been using the same HYCOM tide simulation for the last few years, for the analyses and papers reported on below. This simulation represents a significant improvement over the first HYCOM tide simulations reported on in Arbic et al. (2010), but it is time for a new simulation to be run, and we plan to do one that incorporates the above improvements over the next year.

--Patrick G. Timko, former UM postdoc supported by this grant, currently at University of Bangor in the United Kingdom: Timko is validating the three-dimensional structure of tidal currents and displacements in HYCOM (Timko et al. 2012, 2013, Arbic et al. 2012a) with respect to the current meter observation archive of Scott et al. (2010).

--Malte Müller, former postdoctoral scientist subcontractor from University of Victoria, Canada, currently at Norwegian Meteorological Institute: Mueller was supported by a subcontract from this grant from April 2012 to March 2013, thus helping us to expend funds left over by Timko's earlier-than-anticipated departure for permanent employment in the United Kingdom. Müller worked on two projects with us. First, he utilized the methods of Maik Thomas to develop a full luni-solar tidal potential, analyzed it harmonically to come up with tidal constituents, and adjusted the constituents by frequency-dependent Love numbers to account for solid earth body tide effects. This increases the number of constituents in HYCOM from 8 to 430. This new tidal potential is currently being tested for future implementation in HYCOM tides runs by Alan Wallcraft and Arbic in consultation with Müller. Müller's second and main project with us has been to compute spectra, spectral transfers, and spectral fluxes in frequency-wavenumber space, as a method of diagnosing nonlinear interactions between oceanic motions. Müller is a co-author on Arbic et al. (2013a), which extends the results on nonlinear interactions of gesotrophic eddies in the frequency domain, reported on in Arbic et al. (2012b), to the frequency-wavenumber domain. Müller is revising a related paper (Müller et al. 2013) on frequency-wavenumber diagnostics of nonlinearities in the westward propagation of eddies, and has also begun diagnosis of frequency-wavenumber spectra and nonlinear spectral transfers in the internal wave portion of the HYCOM spectrum.

--Joseph Ansong, postdoctoral scientist, University of Michigan: Ansong, an NSF-funded postdoc, is examining parametric subharmonic instability (PSI) and tidal energy fluxes in the HYCOM tides simulations, in papers in preparation.

--Anna Savage, graduate student in the UM Applied Physics Program: Savage is comparing sea surface height frequency spectra in HYCOM vs. tide gauges, and has also begun using HYCOM to test tidal aliasing issues for the planned wide-swath satellite altimeter mission (SWOT).

--Conrad Luecke, graduate student in the UM Department of Earth and Environmental Sciences: Luecke is working with Arbic, Bassette (see below), and NRL collaborators to compare eddy isopycnal fluctuations in HYCOM with those in historial temperature records. After Luecke and Bassette have published their methodology for model/data comparisons of isopycnal fluctuations, they will constuct global three-dimensional maps of potential and kinetic energy in different frequency bands (geostrophic/mesoscale, near-inertial, and tidal) from our HYCOM simulations.

--Steve Bassette, UM undergraduate math/physics student: Bassette, supported by Arbic's NSF funds, is working with Arbic, Luecke, and NRL collaborators to compare high frequency isopycnal fluctuations in HYCOM with those in current meters.

--Ben Alterman, graduate student in the UM Applied Physics Program: Alterman was supported on this grant for several months from 2012-2013.

--Eric P. Chassignet, FSU, head of HYCOM consortium and keeper of the HYCOM data server: As discussed above and below, we will work with Chassignet on the storage strategy for the server, and on data assimilation of tides into HYCOM.

--Alan J. Wallcraft, NRL, lead PI of related tides grant at NRL: Wallcraft and Arbic collaborated to insert tides into the HYCOM code and continue to consult each other about numerous technical aspects of the tide coding.

--E. Joseph Metzger, NRL: Metzger has been the NRL go-to person for running the HYCOM simulations, and has been extremely helpful to David Trossman, who is conducting NSF-funded HYCOM simulations of the eddying general circulation (more below).

--Maarten Buijsman, NRL: Buijsman has led the re-tuning of the topographic wave drag in HYCOM since joining NRL in the autumn of 2012, and has collaborated on some of the other projects described in this document.

--James G. Richman, NRL: Richman has been an active contributor to most of the projects described in this document, and has taken the lead on examining the impact of internal tides on the wavenumber spectra of sea surface height, a subject of great interest to NASA as it prepares for the wide-swath satellite altimeter. Richman has also begun to ulitize HYCOM to estimate the errors in vertical mode estimation from vertically sparse historical current meter data.

--Jay F. Shriver, NRL: Shriver has also contributed to most of the projects described in this document, and has led global comparisons of HYCOM to the satellite altimeter data of Richard Ray, and an examination of the temporal stationarity of internal tides, both topics of great interest to NASA.

WORK COMPLETED

HYCOM has been run globally with tides at 1/12° and 1/25° resolution. Numerous analyses have been performed on the 1/12° simulations; the 1/25° results are just starting to be looked at. A selection of the most significant results obtained during the last year are described in the following section.

RESULTS

Below we report on results from this past year obtained by Shriver and Richman, Arbic's NRL collaborators, by Timko, Müller, and Joseph Ansong, Arbic's postdocs, and by Savage and Luecke, Arbic's graduate students. Shriver harmonically analyzed one year of output from the HYCOM-with-tides simulations and high-passed the resulting tidal amplitudes to reveal the signature of internal tides at the sea surface. Figure 1 below, taken from Shriver et al. (2012), displays the amplitude of the M_2 signature in both altimeter data (top panel; Ray and Mitchum 1996, 1997; Ray and Byrne 2010) and HYCOM (bottom panel). The figures demonstrate that HYCOM is capturing the hotspots of internal tide generation well. Shriver et al. (2012) confirms this by showing that the HYCOM RMS amplitudes over the hotspot boxes shown in Figure 1 are within about 20% of those in altimeter data for the most important constituents (results not shown here for the sake of brevity). In the HYCOM K_1 results (not shown), there are no internal waves poleward of 30°, as expected from theoretical considerations. The altimeter results contain substantial K_1 activity in western boundary currents poleward of 30°. We interpret this as mesoscale contamination brought about by the relatively poor temporal sampling of the altimeter; the 10 day repeat time of the altimeter aliases tides into the mesoscale band. The K_1 comparison shows that the hourly sampling possible in HYCOM can reveal important limitations in the altimeter data.

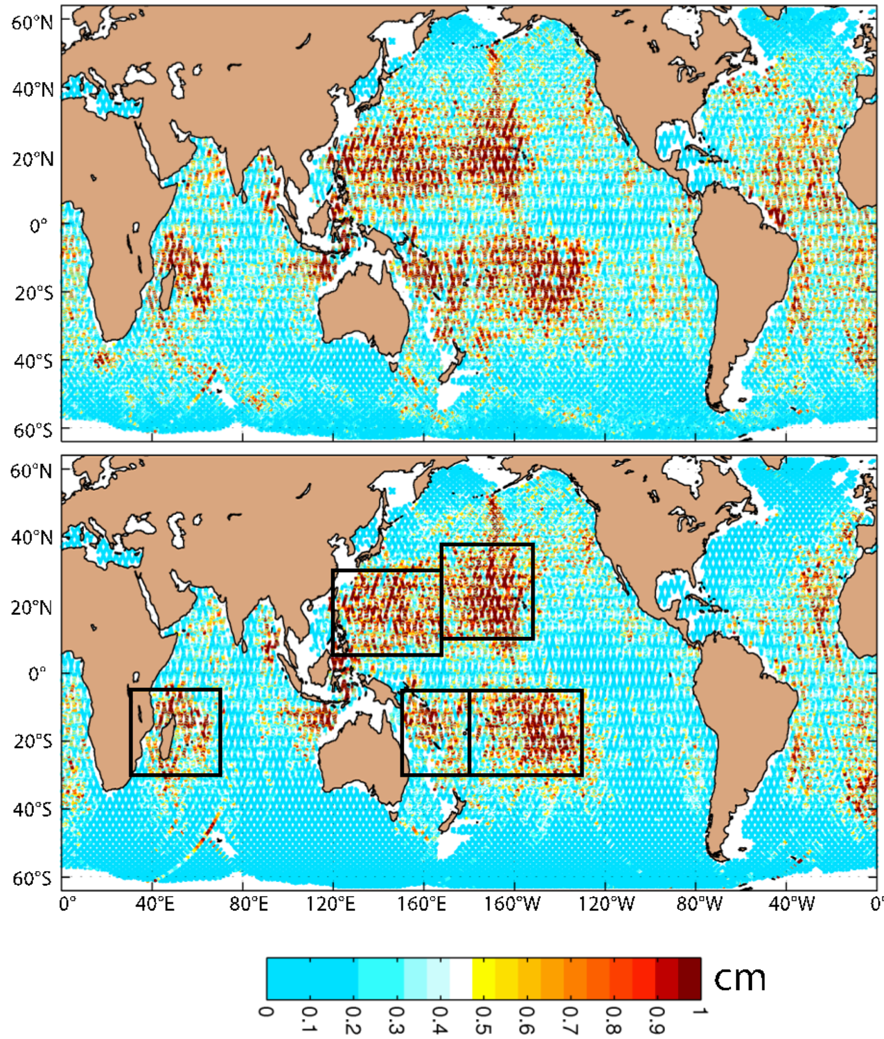

Figure 1: Amplitude (cm) of M_2 internal tide signature in sea surface height, obtained from high-passing the M_2 amplitudes of the full sea surface height. Upper panel: results from along-track satellite altimeter data. Lower panel: results from HYCOM.

After showing that the basic structure of the internal tide field in HYCOM compares well with altimetry, Shriver has moved on to examine the stationarity of HYCOM internal tides (Shriver et al., 2013). Internal tide stationarity in HYCOM and in the ocean is impacted by seasonal effects which alter the oceanic stratification, and by mesocale motions which scatter internal tides. Internal tide stationarity is not only a problem of great scientific interest, but is also important for NASA's planning for the wide-swath satellite altimeter. If internal tide signatures at the sea surface are mostly stationary, then they are removable via standard tidal harmonic analysis. If instead they are mostly non-stationary, then harmonic analysis will not suffice. In Figure 2 we display the non-stationarity as measured by absolute and normalized standard deviations of HYCOM M_2 amplitudes, computed from overlapping 183-day windows of HYCOM output. The absolute standard deviations are generally largest in the hotspot regions. However, in those same regions the normalized standard deviations (standard deviations divided by the mean) are generally fairly small, indicating a large degree of stationarity in agreement with the altimetric analysis of Ray and Zaron (2011).

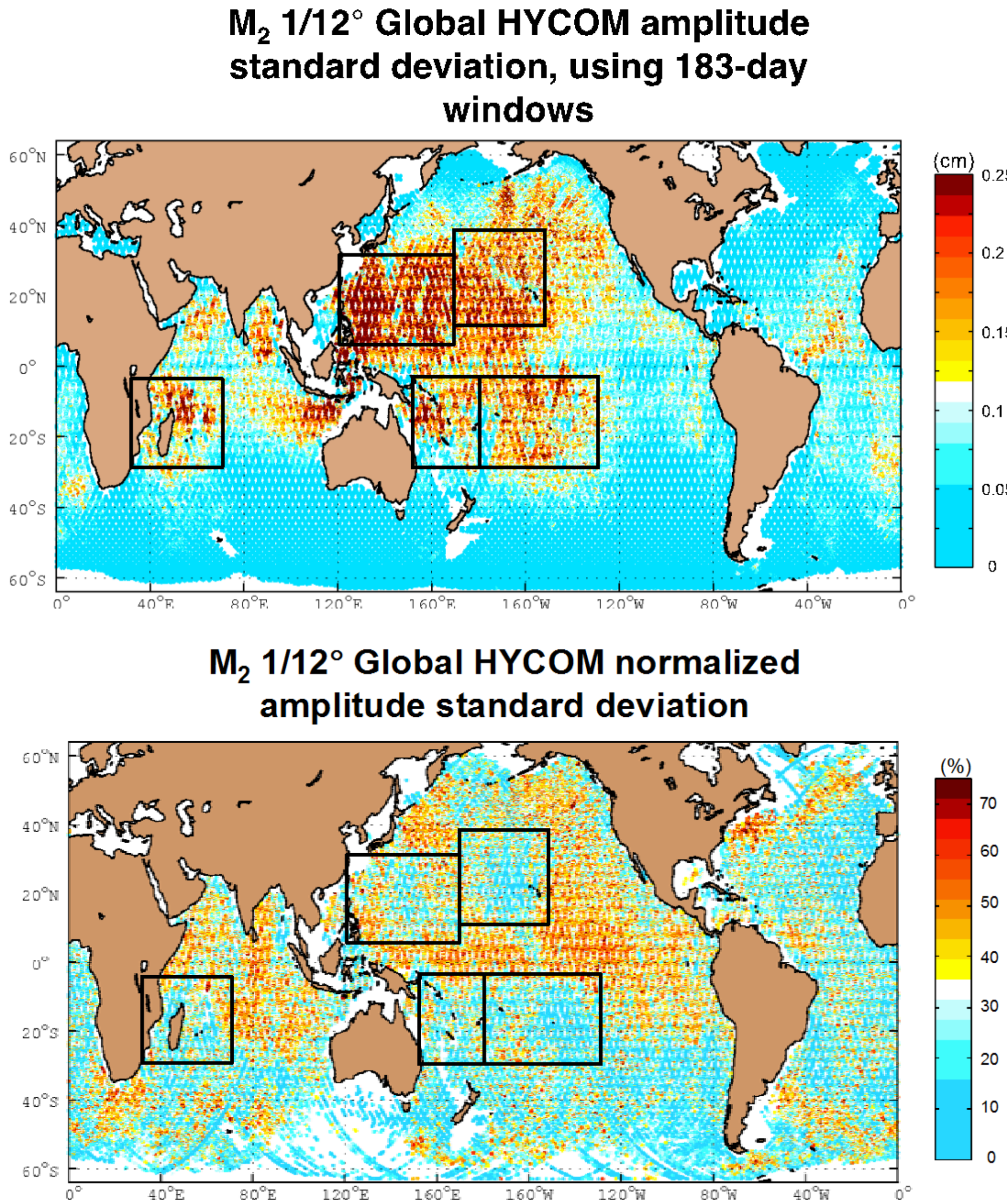

Figure 2: Standard deviation of M_2 internal tide signature in sea surface height, computed from overlapping 183-day windows of HYCOM output put onto altimeter tracks. (Top) absolute value (cm) of standard deviation. (Bottom) Normalized standard deviation, i.e. standard deviation divided by mean amplitudes.

Our NRL collaborator Richman has also taken advantage of the hourly output of HYCOM, to separate the contributions of low and high frequencies to the wavenumber spectrum of sea surface height (Richman et al. 2012). In regions of low internal tide activity, the low frequencies dominate the spectrum (not shown). However, in regions of high internal tide activity, the high frequencies dominate the spectrum, as shown in Figure 3. The implications are that the low-frequency spectrum, which is predicted by surface quasi-geostrophic theory to have a slope of -11/3 (Le Traon et al., 2008), will be buried underneath the high frequency spectrum in regions of high internal tide activity.

Therefore, the internal tide corrections to the wide-swath satellite altimeter data will have to be very accurate to reveal submesoscale dynamics in regions of high internal tide activity.

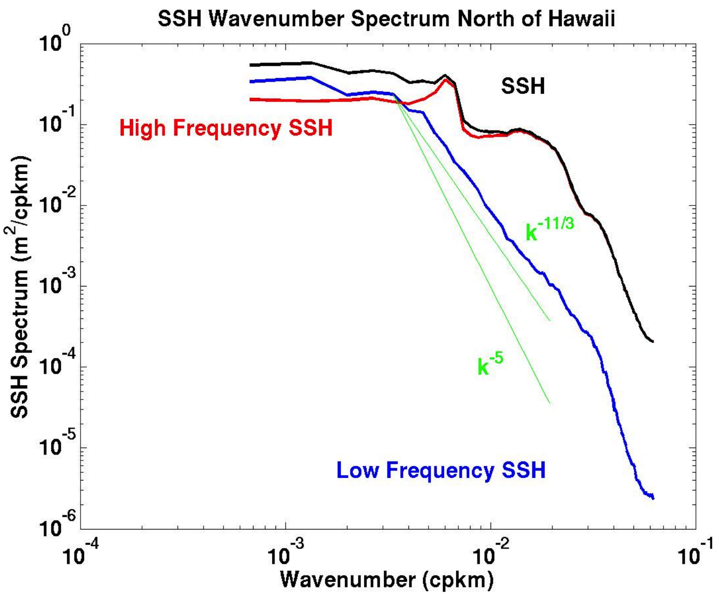

Figure 3: Wavenumber spectrum of steric sea surface height in region of high internal tide activity near Hawai'i. Black/blue/red curves represent spectra of steric height, low frequency steric height, and high frequency steric height, respectively. Extra slanted lines are at theoretically predicted slopes of -11/3 and -5.

Former UM postdoc Timko has compared the global three-dimensional tidal velocity field in HYCOM with available current meter data (Timko et al. 2012, 2013, Arbic et al. 2012a). Timko et al. (2012) develops rigorous criteria for model/data comparisons at individual current meter locations. In general, the diurnal currents in HYCOM are too weak in comparison to observations. This result inspired us to revisit our topographic wave drag. The drag is tuned for M_2, which results in a drag that is too strong for K_1. Our NRL collaborators are currently engineering the wave drag so that it is weaker for K_1 than it is for M_2, in accordance with theoretical considerations (Bell 1975). Figure 4 shows a model/data comparison in a North Pacific location where the model performs particularly well. More generally, Timko et al. (2013; see also Arbic et al. 2012a) find that the semi-diurnal tidal currents in HYCOM match up with those in current meter data reasonably well, as long as substantial averaging is done over both time and space. This can be seen in Figure 5, which displays the locations of the current meters used to compare to HYCOM output, and the vertically averaged kinetic energy over depth bins, in both HYCOM and current meter data.

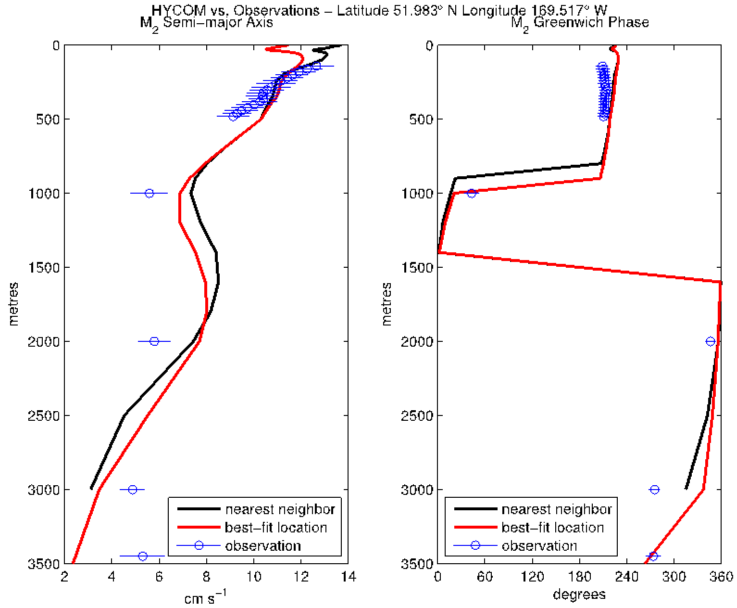

***Figure 4:** Vertical structure of semi-major axis (left) and Greenwich phase (right) of M_2 tidal currents at a particular North Pacific location in ADCP data (blue curves), the nearest model gridpoint in HYCOM (black curves), and from the best fit in eight surrounding model gridpoints (red curves).*

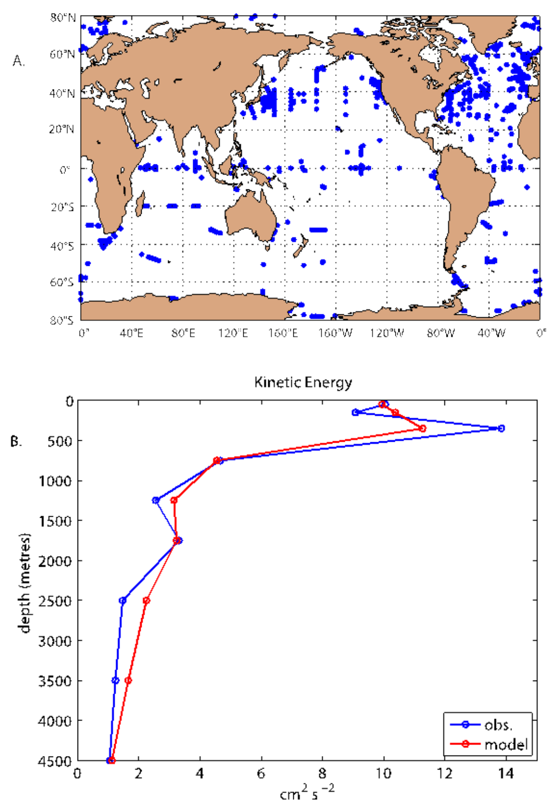

***Figure 5:** (a) Horizonal locations of current meters used to validate the tidal currents in the HYCOM simulations. (b) Vertical distibutions of the M_2 tidal kinetic energy, spatially averaged over depth-binned instruments, for current meter observations and HYCOM simulations.*

Our subcontractor collaborator Müller has computed frequency spectra of upper ocean kinetic energy in the internal wave band for both HYCOM and current meter data. The results, shown in Figure 6, indicate that HYCOM matches the near-inertial and tidal peaks reasonably well. The model match to the high-frequency end of the observed internal wave spectrum is much less good, but increasing the model resolution from 1/12° to 1/25° improves the model-data comparison, at least in some locations. Figure 6 shows that global ocean models are improving in their resolution of high frequency motions in the oceanic spectrum. A paper on the model-data comparisons, and the contributions of nonlinear wave-wave interactions to the model internal wave spectrum, is in preparation by Müller.

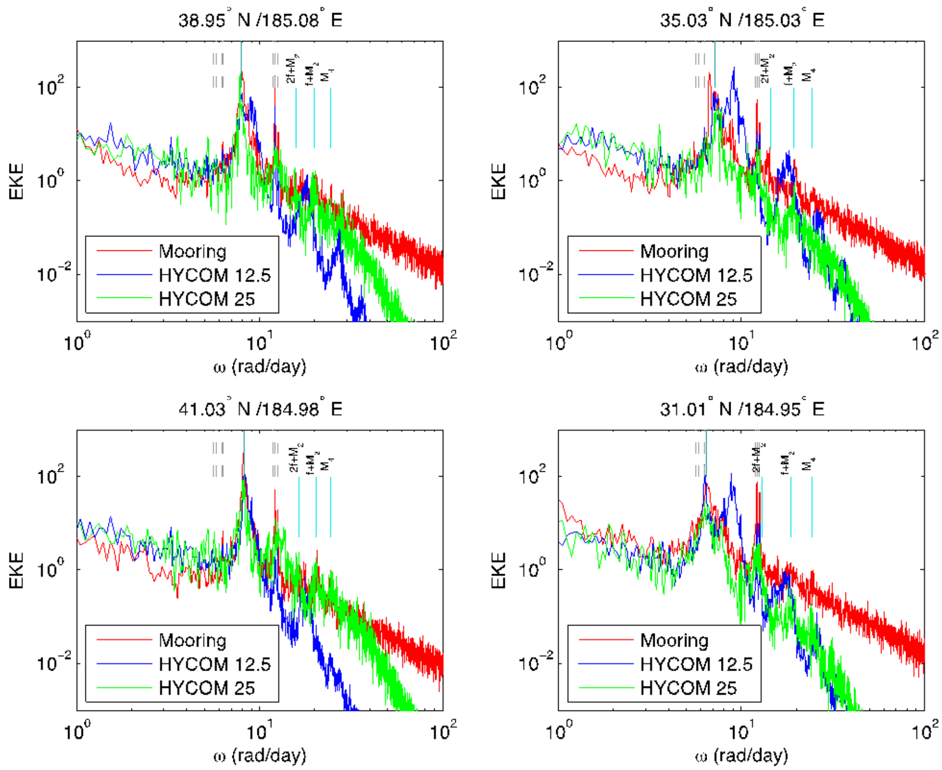

Figure 6: Frequency spectra of kinetic energy in 1/12° and 1/25° HYCOM, compared to spectra from current meters in four locations. Inertial period indicated by dark blue vertical line. Four largest diurnal and four largest semidiurnal tidal periods indicated by dashed vertical lines.

Joseph Ansong, a UM NSF-funded postdoc, has been analyzing the HYCOM results for evidence of parametric subharmonic instability (PSI), a potential mechanism for the breakdown of low-mode internal tides. In Figure 7 we display the bicoherence values at each grid location from the baroclinic velocities obtained from layer 14 (lying at about 500 m depth over much of the ocean) of HYCOM. Both semidiurnal and diurnal results are shown; in each case we show only subharmonic signals having energy at least 1% of that of the primary waves. The results clearly show that PSI is happening primarily at the critical latitudes, as expected. Papers on these PSI results, and on the computed tidal energy fluxes from HYCOM, are currently being prepared by Ansong.

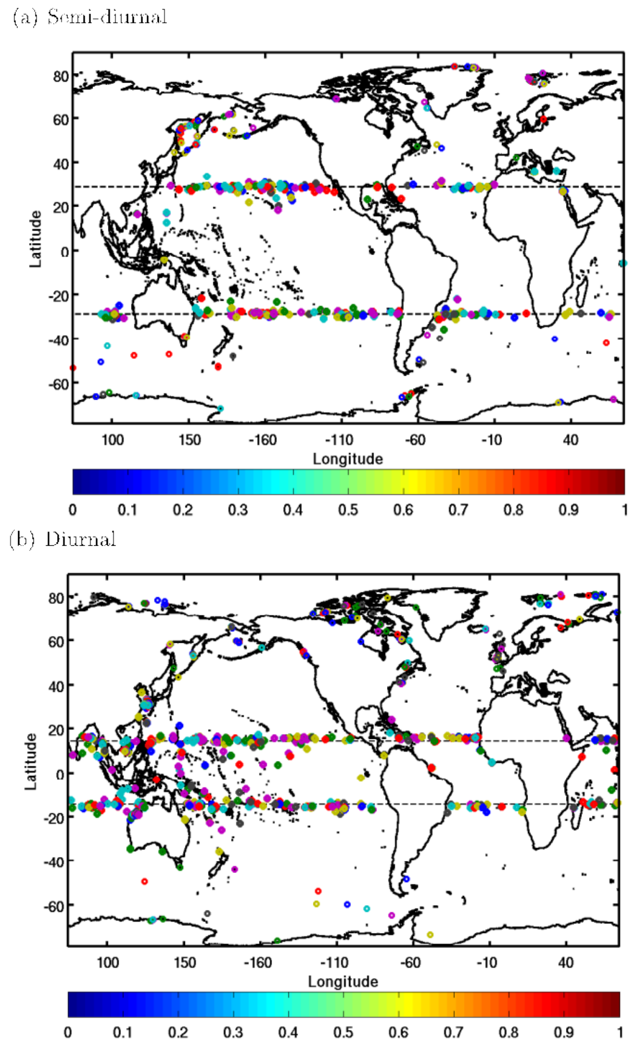

Figure 7: Significant bicoherence values at each grid location from the baroclinic velocities in layer 14 (laying at about 500 m over much of the ocean) from HYCOM. Only locations at which the subharmonic energy is at least 1% of the primary waves are shown.

In Figure 8, we display an example sea surface height frequency spectra comparison in HYCOM versus a tide gauge record, from a paper in preparation by UM graduate student Anna Savage. The figure demonstrates that HYCOM matches the observations reasonably well at low frequencies (periods longer than a few days), and at tidal frequencies (predominantly one and two cycles per day). The model-data comparison is less good at periods lower than about 4 hours. Likely reasons for the mismatch at the highest frequencies shown include the inability of the model to resolve all of the internal wave spectrum, and instrumental noise in the tide gauges.

UM graduate student Conrad Luecke, and NSF-supported UM undergraduate Steve Bassette, are comparing the ispoycnal displacements in HYCOM to those in moored historical temperature records. Since the historical records do not usually contain salinity, we use temperature as a proxy for density, and we employ a consistent analysis of the model and the historical data. The left-hand panel of Figure 9 displays the Brunt-Väisälä frequency N^2, spatially averaged over a subset of 170 mooring locations in HYCOM and in the 2009 World Ocean Atlas (a much larger dataset will be employed for

this calculation in the near future). The model stratification compares reasonably well with the observed World Ocean Atlas stratification, in the spatial average. The right-hand side of Figure 9 displays the low-frequency eddy available potential energy (i.e., the available potential energy anomaly), computed from the "APE_3" formula of Kang and Fringer (2010), i.e. g^2 rho'^{2} / 2 rho$_0$ N^2, where g is gravitational acceleration, rho' = - alpha T' is the low-frequency density anomaly computed from the thermal expansional coefficient alpha and the low-frequency temperature anomaly T' from the time mean temperature, and rho$_0$ is an average seawater density. Although the point-to-point model-data APE comparison displays considerable scatter, the scatter lies on both sides of the one-to-one line indicating little bias in the model. HYCOM is thus able to reproduce the ocean's low-frequency eddy available potential energy field reasonably well. Bassette's work in progress is examining the high-frequency availalble potential energy fields in HYCOM and in historical temperature records. Papers on the low-frequency and high-frequency available potential energy anomalies in HYCOM versus observations are currently in preparation by Luecke and Bassette, respectively.

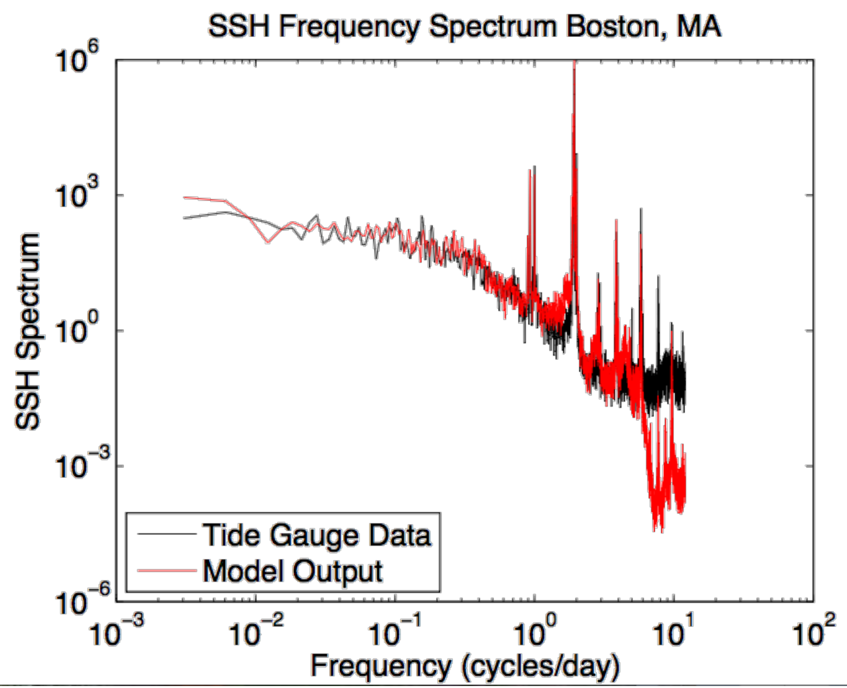

Figure 8: Sea surface height frequency spectra from HYCOM (red) and a tide gauge (black) at Boston.

IMPACT/APPLICATIONS

The tidal research is driven by the stated need for NAVOCEANO to have tides and data assimilation in 1/25° HYCOM, for operational purposes.

The wavenumber spectrum calculation done in Richman et al. (2012) was done at the request of the wide-swath satellite altimeter PIs (Lee-Lueng Fu, Rosemary Morrow, Ernesto Rodriguez). Richman's results were used in the planning of the locations for the AirSWOT test mission (Ernesto Rodriguez, personal communication 2011). The work of Shriver et al. (2012, 2013) and of graduate student Anna Savage is also of interest to SWOT. Arbic, Shriver, and Richman are co-PIs on NASA SWOT grant NNX13AD95G, which is supporting Anna Savage's summer salary.

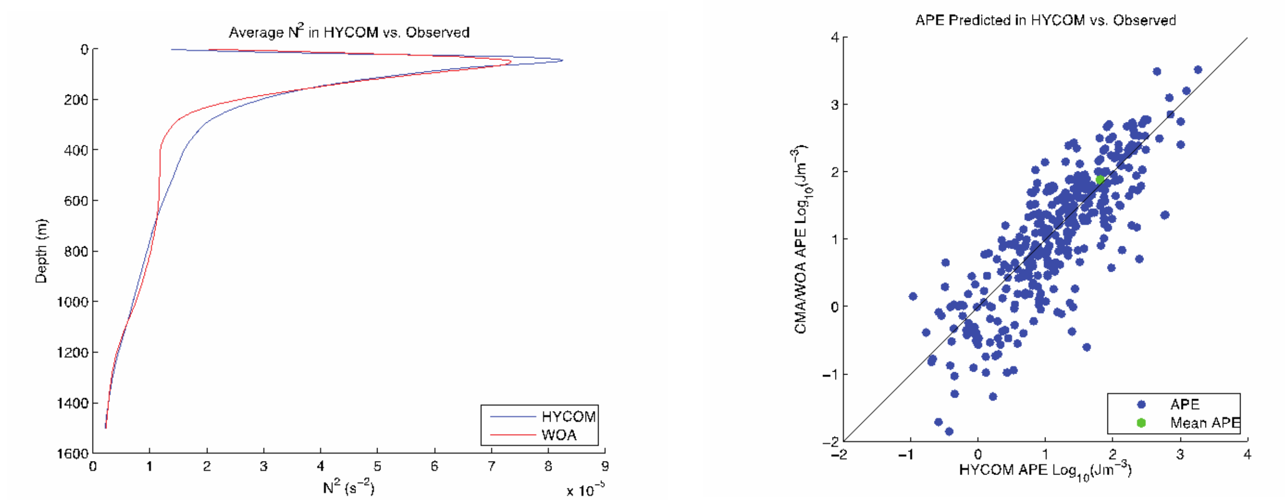

Figure 9: Left: spatially averaged profiles of N^2 in HYCOM versus 2009 World Ocean Atlas (Antonov et al. 2010; Locarnini et al. 2010), averaged over 170 locations of historical moored temperature measurements. Right: Scatter plot of low-frequency eddy available potential energy computed from HYCOM versus historical moored temperature data at the same 170 locations.

TRANSITIONS

The work reported on here is an important part of a planned transition by the NRL Stennis Space Center ocean modeling group from forecasts that are based on NLOM (Naval Research Laboratory Layered Ocean Model) to HYCOM. Tides are among a number of improvements in the HYCOM simulations compared to the NLOM simulations.

RELATED PROJECTS

The work reported on here is strongly tied to the HYCOM tides grants currently in place at FSU (led by Eric Chassignet) and at NRL (led by Alan Wallcraft). Arbic has been working closely with Wallcraft and other NRL personnel (Buijsman, Metzger, Richman, Shriver) since 2006 to implement and validate tides in HYCOM. Arbic has continued to work closely with NRL collaborators as the papers listed below under "Publications thus far, resulting from current grant" and "Publications from previous NRL subcontract to PI" are submitted and published. More studies and papers are planned, and the close collaborations will continue. Arbic will work closely with NRL collaborators and with Chassignet to decide how best to store simulations with embedded tides on FSU's data server. Tidal data is traditionally stored hourly, but hourly three-dimensional global output from HYCOM will likely overwhelm any server at FSU. As we have been doing with the simulations thus far, we will decide on sampling strategies to best handle this problem. Thus far, for instance, we have been saving 1) daily averages of three-dimensional global output, 2) three-dimensional global output at hourly intervals over the timespan of one month, 3) selected variables, such as sea surface height and surface velocities, at hourly intervals over several years, 4) selected regions of interest, such as Hawai'i and the Philippines, at hourly intervals and at full three-dimensional spatial resolution. We will discuss similar strategies for the FSU data server.

The work reported on here was leveraged to obtain two NSF grants, both involving multiple institutions. The focus of one NSF grant is the impact of bottom boundary layer drag and topographic wave drag on low-frequency motions such as mesoscale eddies and western boundary currents. The UM postdoc employed on this grant, David Trossman, has obtained computer accounts on NAVO and ERDC machines, as well as 20,000,000 core hours on the new Yellowstone NCAR machine, and is working closely with Joe Metzger and Alan Wallcraft. As expected, the wave drag impacts the model energy budgets significantly. This work should therefore be beneficial for overall HYCOM development. The other NSF grant is a Climate Process Team (CPT) grant led by Jennifer MacKinnon of Scripps and focused on developing better parameterizations of internal-wave driven mixing for ocean models. This project involves many internal wave experts (Polzin, St. Laurent, Alford, Simmons, Kunze, Gregg, MacKinnon, Legg, Klymak, Pinkel), most of whom work on Navy-funded projects. One of the four postdocs funded by this CPT, Joseph Ansong, is based at UM and is analyzing the HYCOM with tides simulations reported on here for the NSF work. Specifically he is examining parametric subharmonic instability in the model (Simmons 2008), and has been computing barotropic-to-baroclinic energy conversions as in Simmons et al. (2004), but under more realistic conditions such as the prsence of eddies and of horizontally varying stratification. Ansong has visited Simmons, Alford, and Gregg in order to facilitate better communication, and will be giving a seminar a UW/APL in October 2013 at the invitation of Kunze. The results of Ansong's NSF-funded research, like those of Trossman's, are anticipated to be beneficial to overall HYCOM development, and to the HYCOM-with-tides project reported on here.

In addition, Arbic has utilized his connections to NRL investigators to investigate eddy dynamics in NRL models (NLOM and HYCOM), leading to papers on the bottom boundary layer drag dissipation of the low-frequency general circulation (Arbic et al. 2009), a paper on comparison of HYCOM vs current meter kinetic energies at low frequencies (Scott et al. 2010), and four papers motivated by present-day and planned wide-swath altimeter missions—Arbic et al. (2012c), which investigates the effect of stencil width on computations of geostrophic velocities from altimeter data, Arbic et al. (2012b), which investigates nonlinear interactions in the frequency domain, Arbic et al. (2013a), which investigates nonlinear interactions in the frequency-wavenumber domain, and Arbic et al. (2013b), which investigates the impacts of eddy viscosity and horizontal resolution on the forward energy cascades to high wavenumbers computed from models and altimeter data.

We conclude with four additional brief notes of interest: First, as anticipated, Patrick Timko, who was funded by this ONR grant, was instrumental in helping to get UM postdocs Trossman and Ansong up to speed on their NSF-funded HYCOM projects. Second, Timko has moved on to permanent employment, as a project scientist for the SEACAMS project based out of the University of Bangor, United Kingdom. Third, Müller has also moved on to a permanent position, at the Norwegian Meteorlogical Institute. Fourth, since Ansong is from sub-Saharan Africa, he represents a member of an under-represented group working on HYCOM. However, since he is funded by an NSF grant, I did not count him as a minority postdoc working on this ONR grant. Fifth, Steve Bassette, a UM undergraduate performing Navy-related (but NSF-funded) research on HYCOM, is a U.S. Navy veteran.

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